Space Technology 6 Autonomous Sciencecraft Experiment Validation & EO-1 Sensorweb Demonstrations

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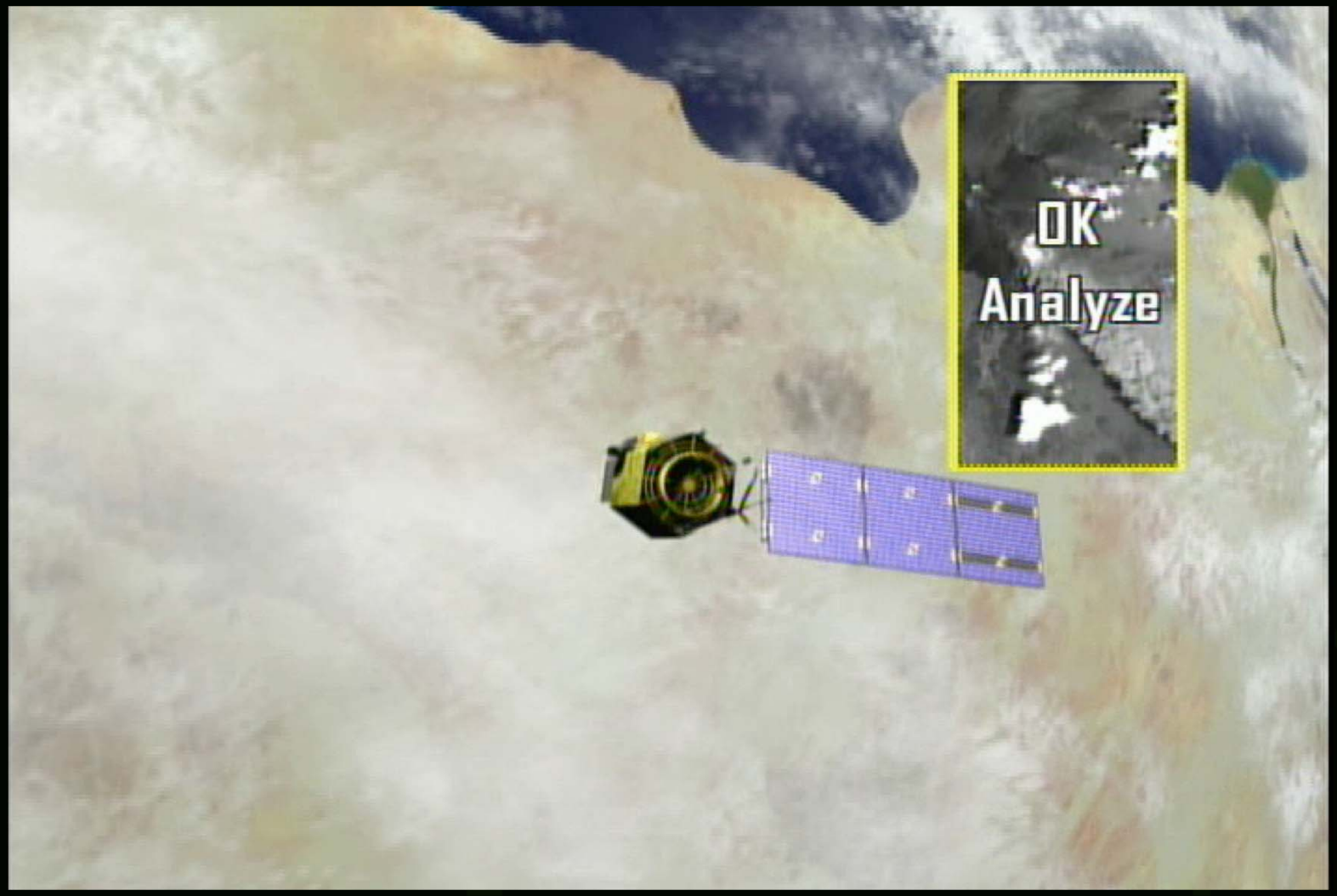
June 28, 2006

Outline

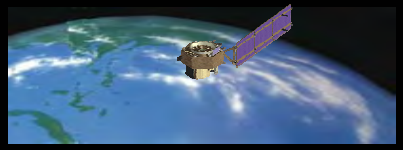
- Autonomous Sciencecraft (ASE) on EO-1
  - Experiment Description and Examples
  - ASE Science Scenarios
  - Changes in EO-1 Operations
- EO-1 Sensorweb
- Future Work
- Conclusions

Autonomous Sciencecraft Scenario



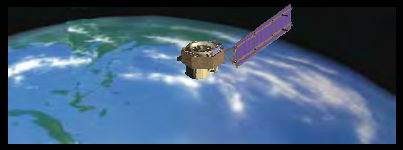
Autonomous Sciencecraft

Image taken by Spacecraft



Science Response

Image taken by Spacecraft

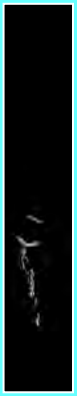


Onboard Science Analysis

Event Detection

No event Detected: Delete Image

Event Detected



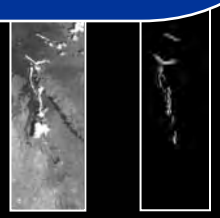
ASE uses state of the art Machine Learning to detect events in the presence of noise

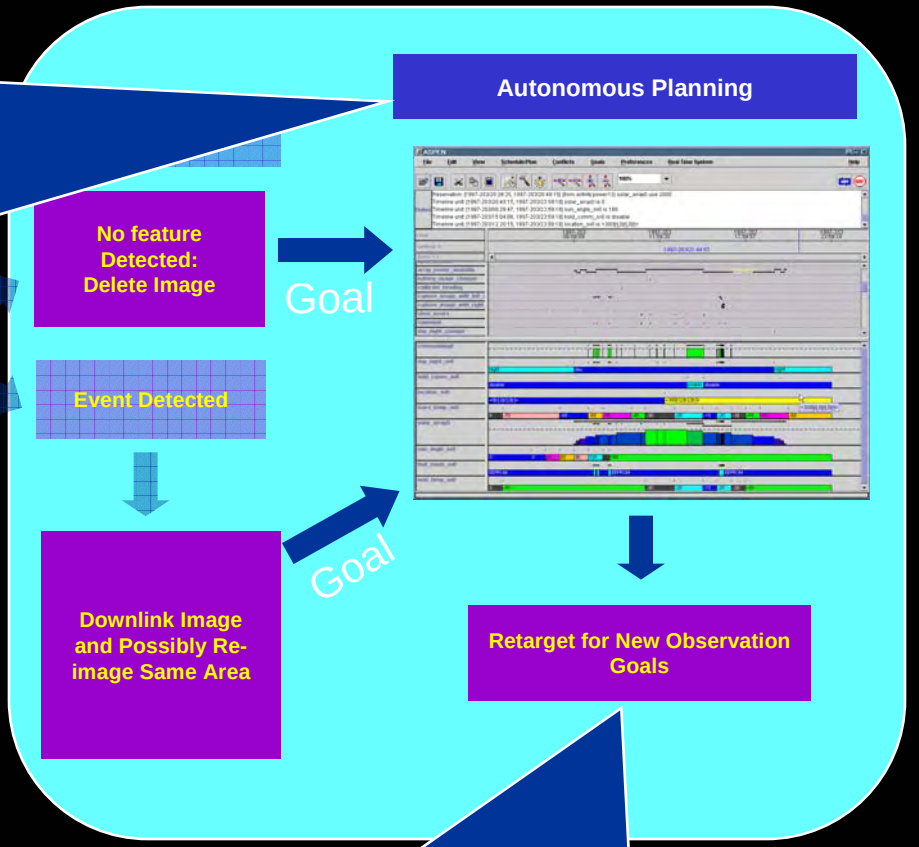
Track a wide range of science events – floods, volcanoes, cryosphere changes, clouds,…

Key Insight: No need to replicate ground science analysis – just detect activity

Science Response

continuous planning - enables seamless long-duration operations and rapid replanning despite limited onboard CPU





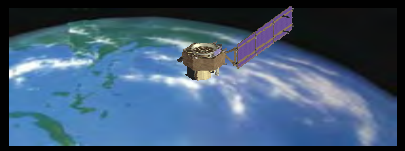
Onboard planning enables rapid response to detected event

Science Response

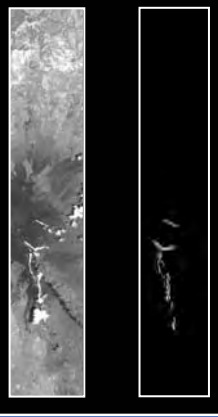
Onboard Science Analysis

Autonomous Planning

Image taken by Spacecraft



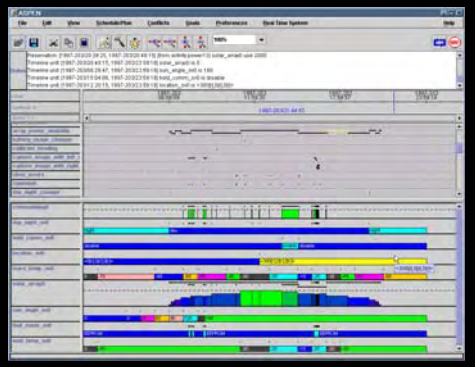
Land Feature Detection



No feature Detected: Delete Image

Feature Detected

Downlink Image and Possibly Re-image Same Area



Retarget for New Observation Goals

New Science Images

Autonomous Execution

Event-driven execution of response image

Technology Carrier: EO-1 Mission

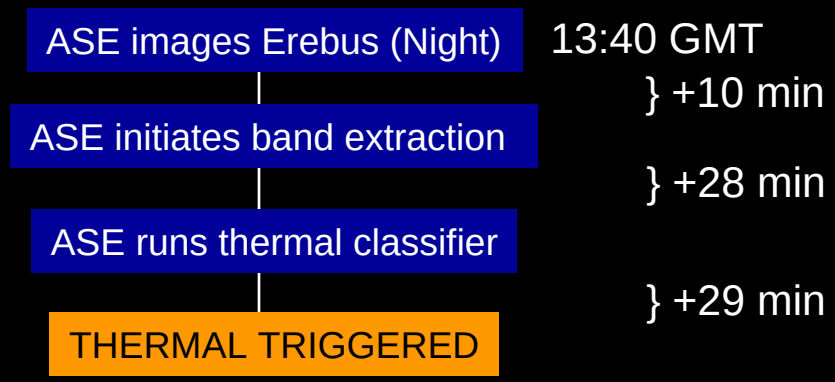
- ASE started as a technology experiment
  - Part of the NASA New Millennium ST-6 Project
  - Subsystem demonstration
  - Funded to flight demonstrate autonomy software technology for future mission adoption
  - Uses Hyperion instrument onboard EO-1 (hyper-spectral, 220 bands, 30 m resolution)

- EO-1 Command Data Subsystem
  - 2 Mongoose V CPU's @ 8 MIPS and 256 MB RAM
  - Flight control software on main CPU
  - Autonomy software on solid state data recorder CPU

Hyperion Imager

Advanced Land Imager

7 May 2004 ASE monitors Mt. Erebus



7 May 2004 ASE monitors Mt. Erebus

ASE images Erebus (Night) — 13:40 GMT

} +10 min

ASE initiates band extraction

} +28 min

ASE runs thermal classifier

} +29 min

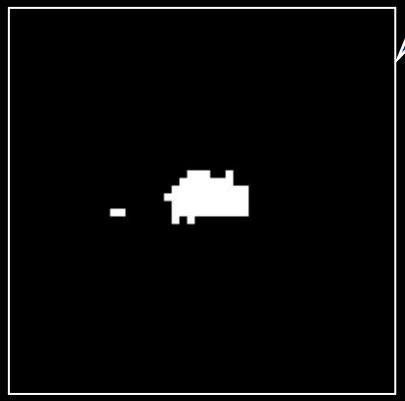
THERMAL TRIGGERED

Planner selects reaction observation (Stromboli observation replaced)

} +20 min

Thumbnail downlinked (S-band) — 15:58 GMT

ASE Onboard Thermal Classifier Thumbnail (Erebus Night)



+ 2 hours 18 minutes

7 May 2004 ASE monitors Mt. Erebus

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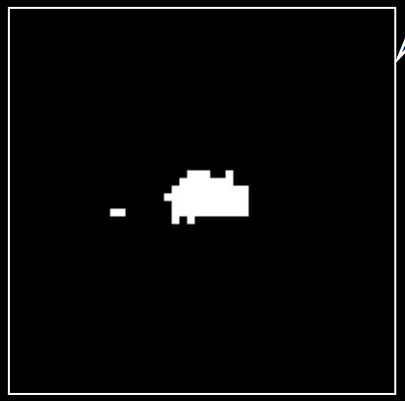
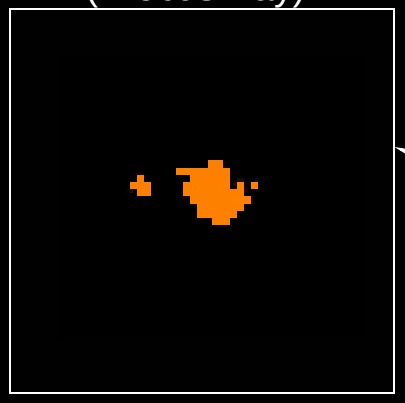
ASE images Erebus again — 20:10 GMT

ASE Onboard Thermal Classifier Thumbnail (Erebus Night)



+ 2 hours 18 minutes

ASE Onboard Thermal Classifier (Erebus Day)



+ 6 hours 30 minutes

7 May 2004 ASE monitors Mt. Erebus

ASE images Erebus Night — 13:40 GMT

} +10 min

ASE initiates band extraction

} +28 min

ASE runs thermal classifier

} +29 min

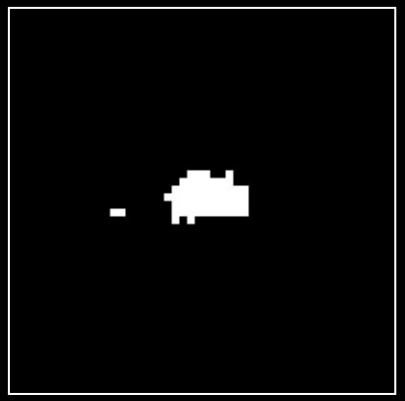
THERMAL TRIGGERED

Planner selects reaction observation (Stromboli observation replaced) — } +20 min

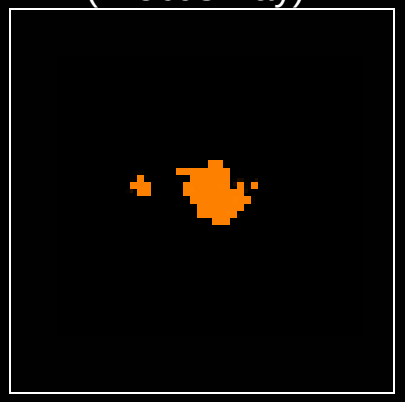
Thumbnail downlinked (S-band) — 15:58 GMT

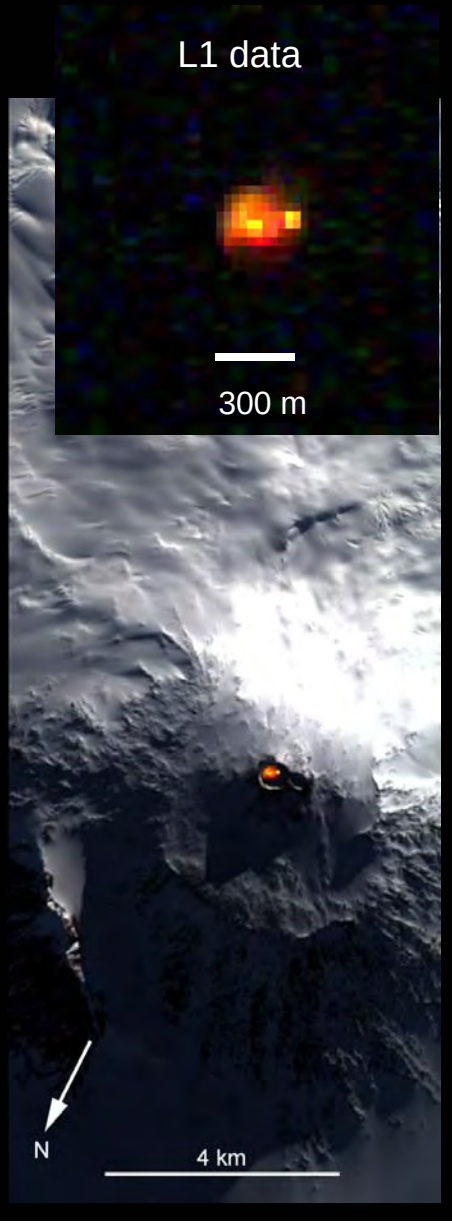
ASE images Erebus again — 20:10 GMT + 06:30

ASE Onboard Thermal Classifier Thumbnail (Erebus Night)



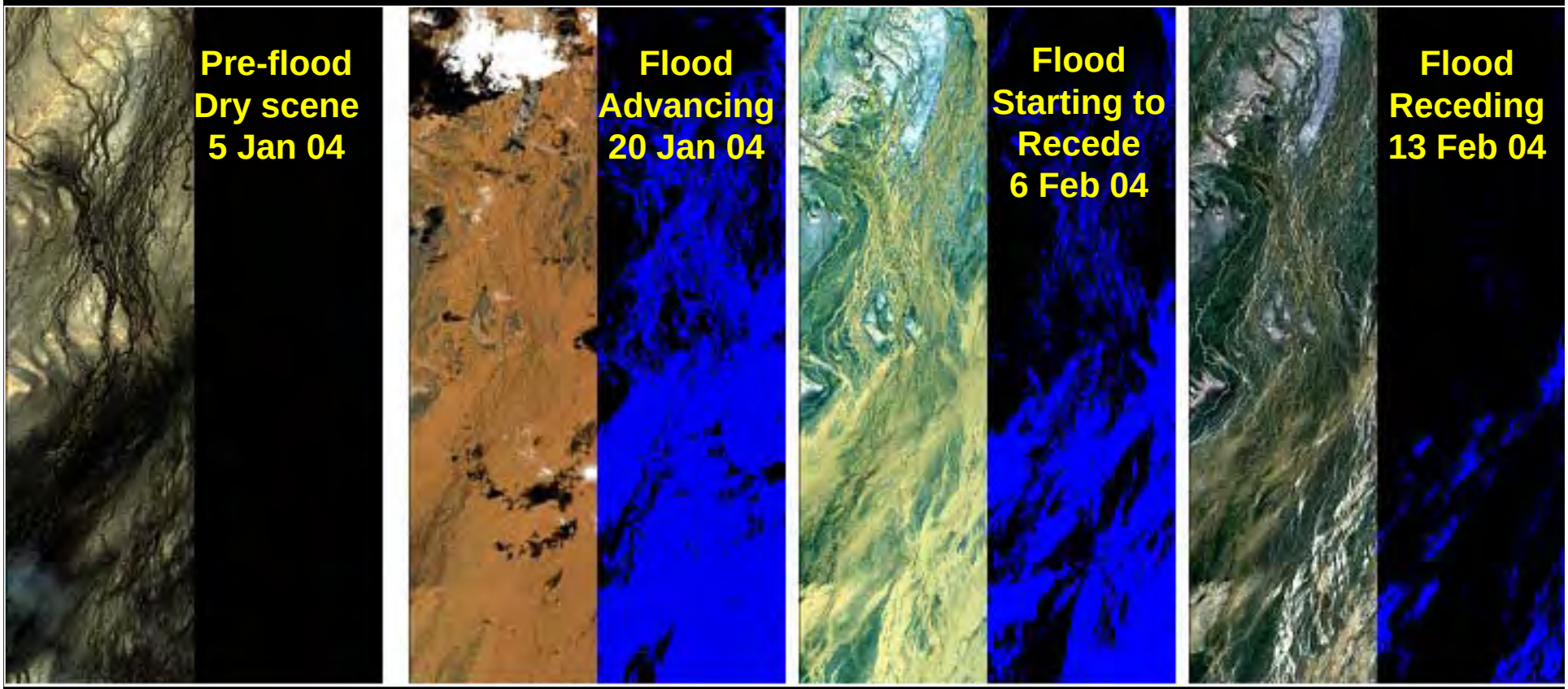
ASE Onboard Thermal Classifier (Erebus Day)





- ASE enabled rapid notification of volcanic event
- ASE enabled rapid re-imaging of this event
- The autonomous response is part of normal operations.

Detection of a Rare Major Flood on Australia's Diamantina River using the ASE "Muddy" Floodwater Classifier



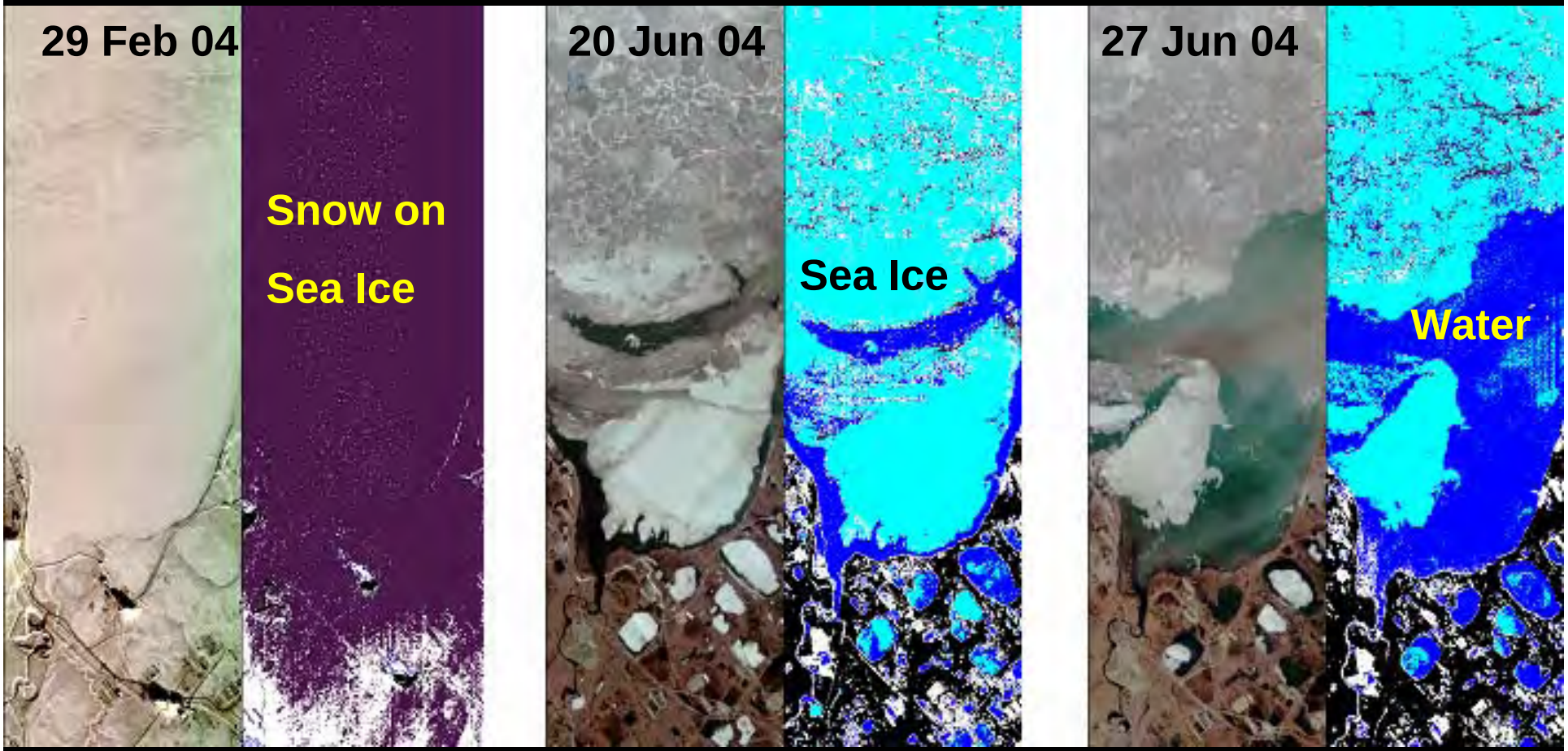
Cause of flooding: Monsoonal rain

Wavelengths used: 0.86 µm and 0.99 µm

V. Baker, F. Ip, & J. Dohm, University of Arizona

Cryosphere Classifier

Deadhorse (Prudhoe Bay), Alaska



Snow
Water
Ice
Land
Unclassified

Wavelengths used in classifier:
0.43, 0.56, 0.66, 0.86 and 1.65 µm

R. Greeley & T. Doggett
Arizona State University
Planetary Geology Group

Software Reuse

- ASE provides excellent baseline to measure model-based software reuse
  - Techsat-21 operations software adapted to EO-1 operations
  - Main same components also flown on Three Corner Sat (3CS)

Module	EO-1 code	Reused from TS-21	Reuse
CASPER Flight	223	200	90%
SCL Flight	214	200	93%
Science Flight	50	0	0%
Ground Automation	25	0	0%
Testing	40	20	50%
Total	**593**	**420**	**71%**

* In thousands of lines of code

Old Way of operating EO-1

Science Team selects targets

Preliminary ground contacts determined

Sun	Mon	Tue	Wed	Thu	Fri	Sat
Sun	Mon	Tue	Wed	Thu	Fri	Sat
Sun	Mon	Tue	Wed	Thu	Fri	Sat

- Manual meetings, assisted by excel spreadsheet
- Check only small subset of observation constraints

Old Way of operating EO-1

Sun	Mon	Tue	Wed	Thu	Fri	Sat
Sun	Mon	Tue	Wed	Thu	Fri	Sat
Sun	Mon	Tue	Wed	Thu	Fri	Sat

- Resolve observation conflicts manually
- Requires all parties (science & engineering) present

Old Way of operating EO-1

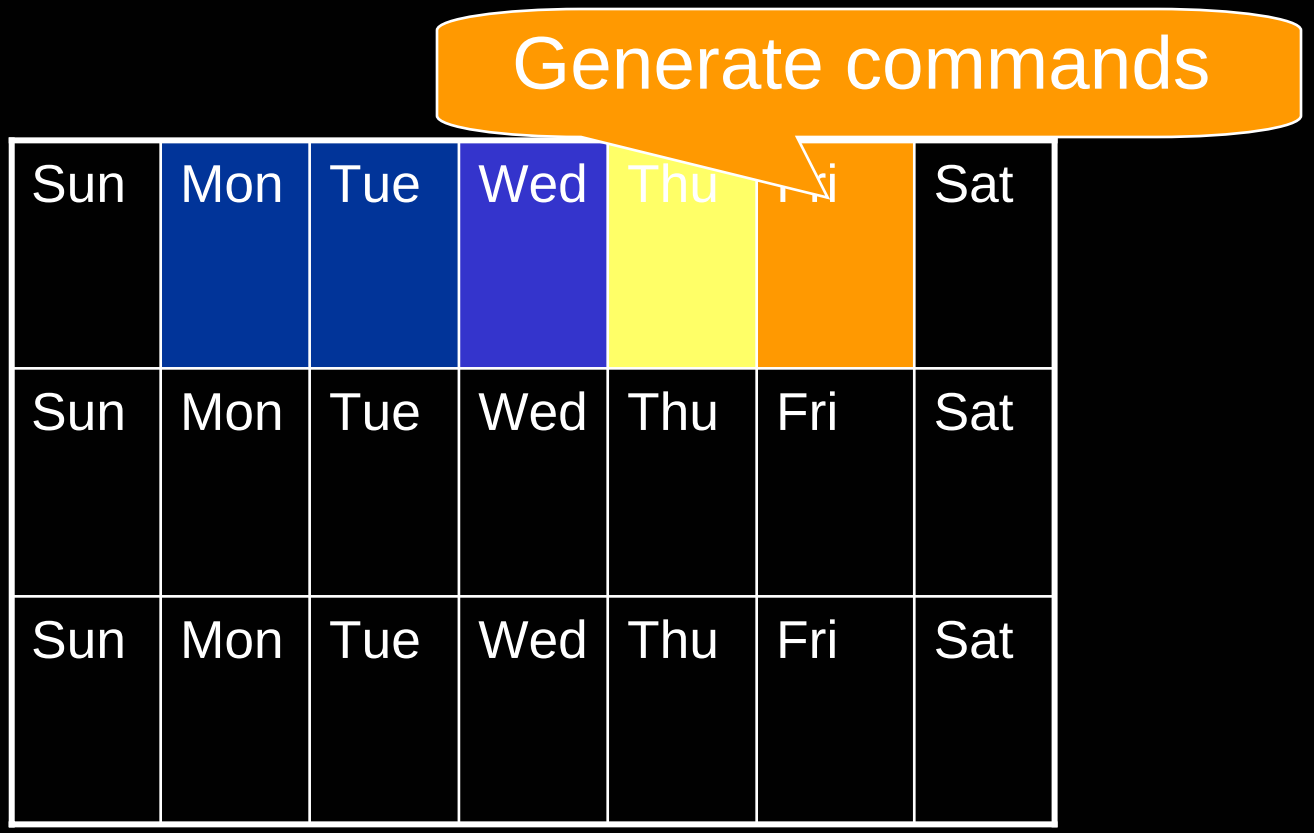
Generate baseline weekly observations

Finalize ground contacts

Sun	Mon	Tue	Wed	Thu	Fri	Sat
Sun	Mon	Tue	Wed	Thu	Fri	Sat
Sun	Mon	Tue	Wed	Thu	Fri	Sat

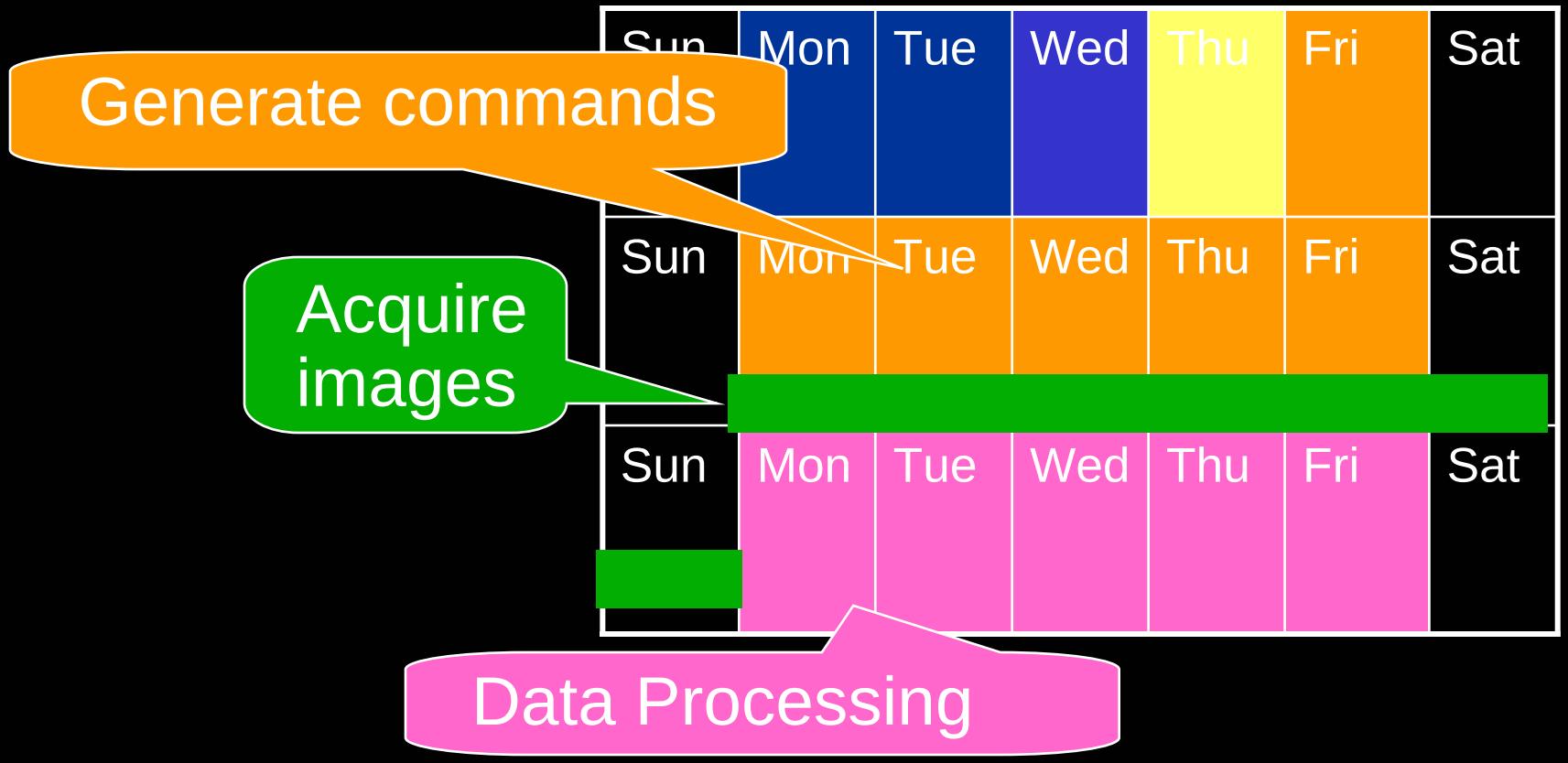
- Identifies most operations conflicts
- Often requires re-work of key days in schedule

Old Way of operating EO-1



- Operations begins with generation of command loads
- Each day is generated on last prior working day
  - e.g. FRI generate for SAT, SUN, MON (SAT & SUN picked prior week)

Old Way of operating EO-1



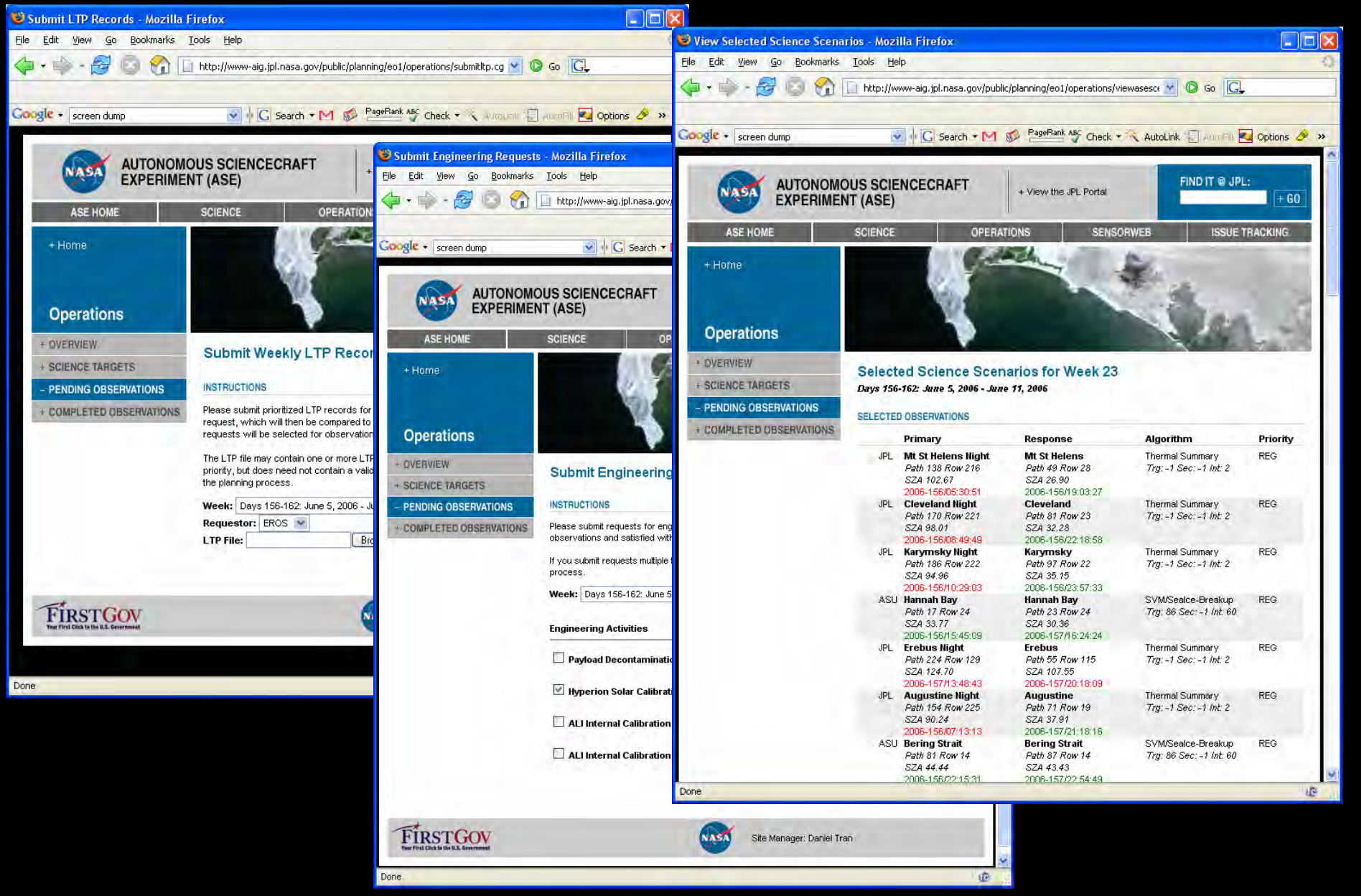
Generate commands last working day prior to acquisition
Downlink & Processing : ~5 working days

Total: ~ 14 days for nominal science loop

New Operations Process

- Less labor-intensive
  - Science and engineering requests are submitted 1 week ahead of time using the web (distributed)
  - Conflicts are *resolved automatically* using automated planning software
    - Observational constraints checked
    - Ground contacts generated
- Closes the science loop *faster*
  - Last minute requests can be submitted a few hours before uplink, resulting in science products within hours
  - It was possible using the old operations process to submit last minute requests 1-2 days in advance, but it required the mission planning team to completely replan the days events

New Operations Process

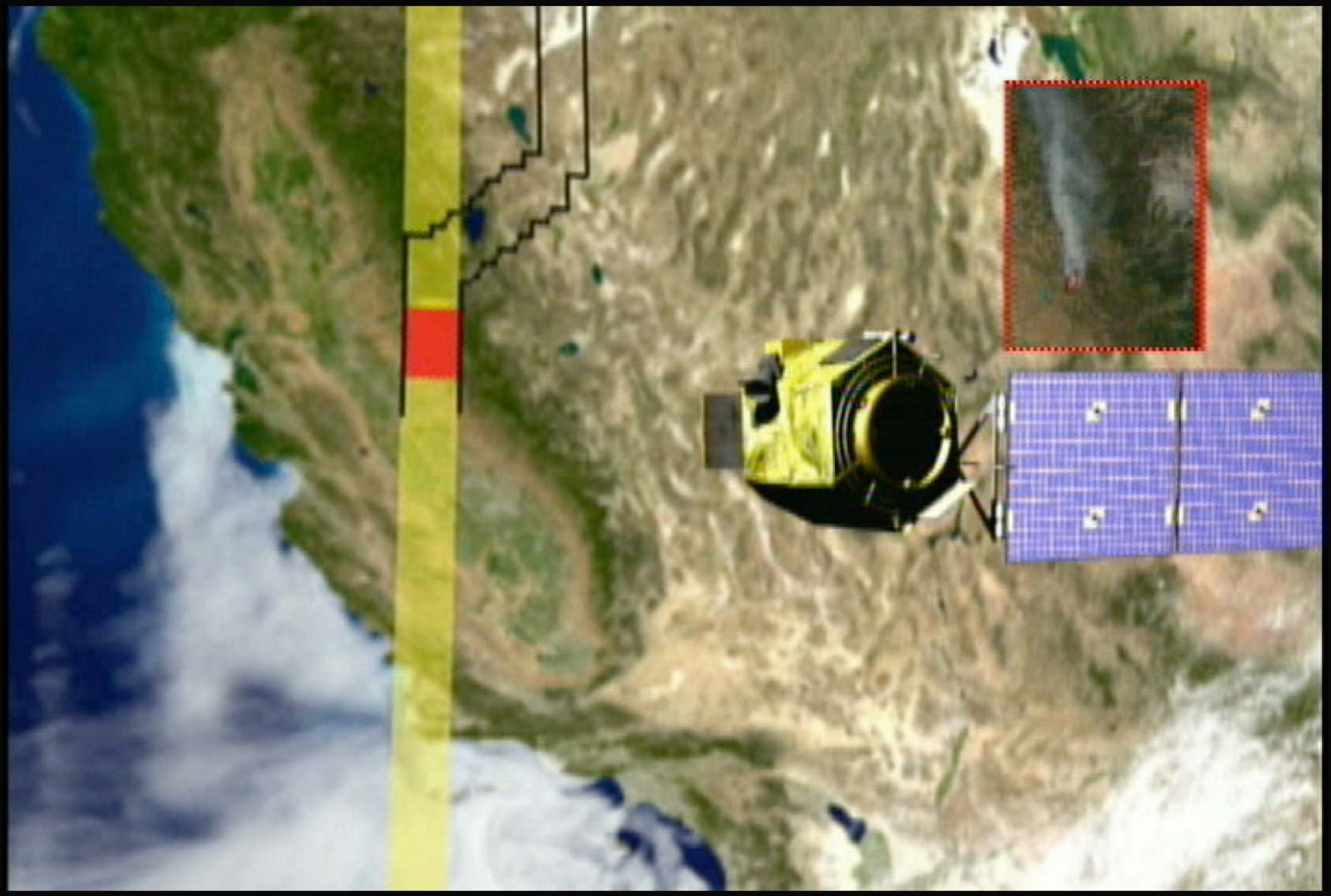


ASE Current Status

- ASE achieved 100% of its Experiment Full Success Criteria in May 2004
  - This includes multiple (5 each) successful:
    - On-orbit autonomous detection & response observations
    - Onboard data editing and data downlink
- Current count 6000+ autonomous data collects
  - Initial flight experiments in Fall 2003
- ASE Software so successful it is now in use as baseline operations for the remainder of the mission (Nov 2004-)
  - Enabled > 100x increase in science return
    - Measured as: # events captured / MB downlink
  - Enabled a reduction in net operations costs from $3.6M/year to $1.6M/yr
    - Over $1M of reduction directly from ASE
- Operations cost reduction critical in enabling extended mission
  - From Oct 2005 – Oct 2007
- ASE co-winner NASA Software of the Year for 2005*
- ASE extended to multiple spacecraft and ground sensors to form a sensorweb

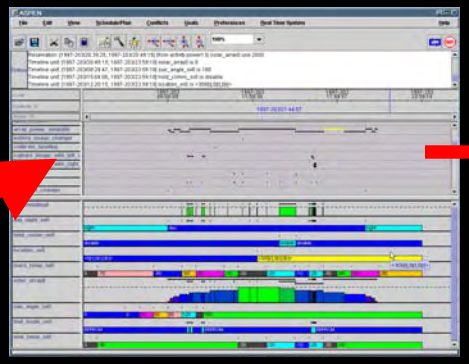
* Other winner was GSFC Land Information System (LIS)

The Earth Observing One Sensorweb



Sensorweb

Re-tasking

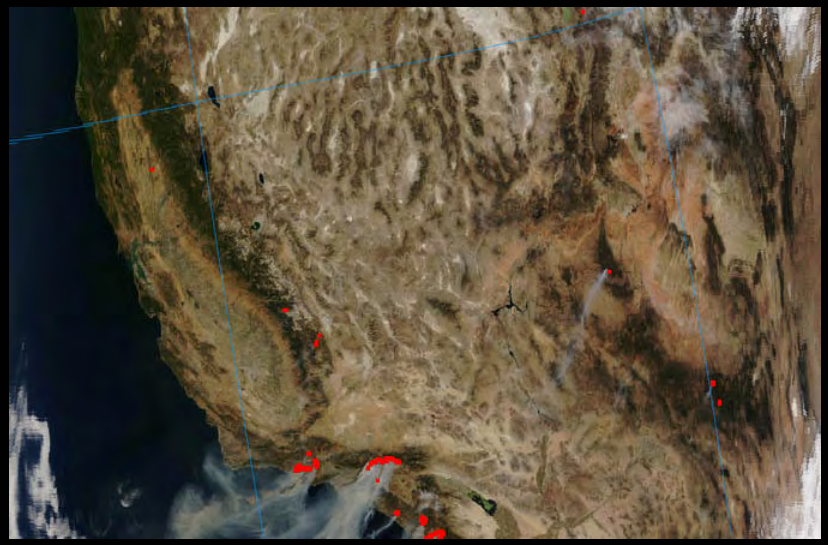


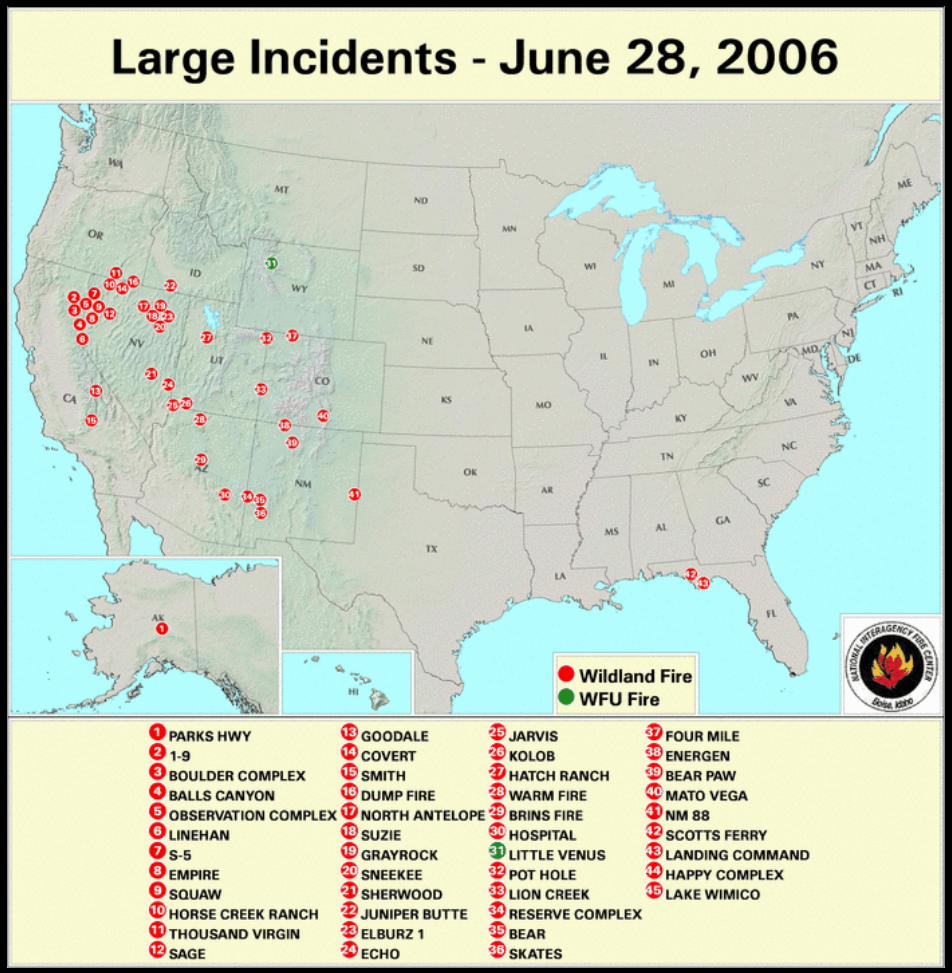
Earth Observer One

Triggers so far: Wildfires, Floods, Volcanoes (thermal, ash), Ice/Snow, in-situ sensors, modified by cloud cover

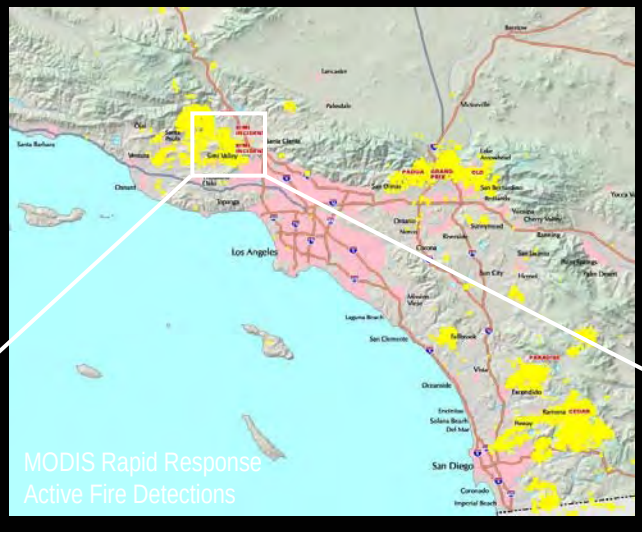
Wildfires

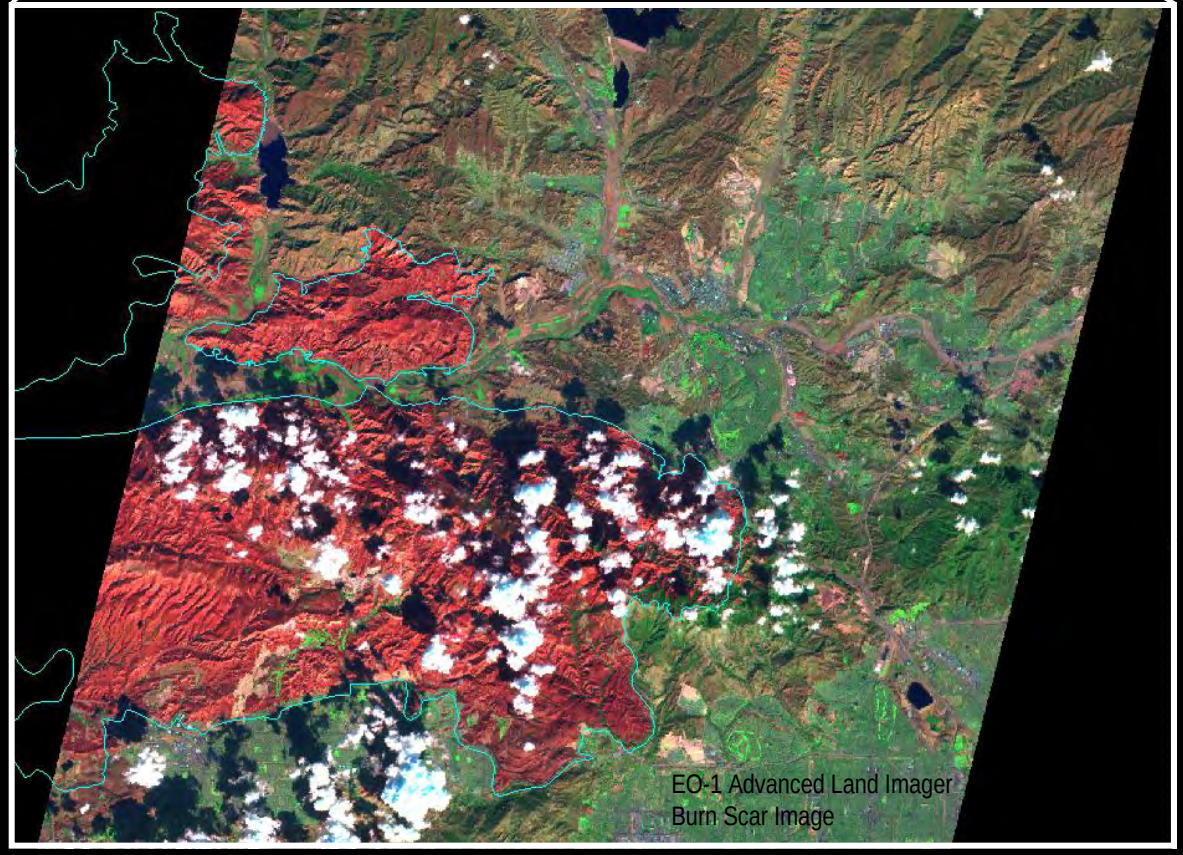
- Triggered from MODIS Active Fire Alerts
  - Fire information products are compiled twice daily at the USDA Forest Service (USFS) Remote Sensing Applications Center
- Uses data from GSFC Distributed Active Archive Center (DAAC)
  - ~ 3-6 hours from acquisition, uses predicted ephemeris





Wildfire SensorWeb





On 11-2-03, the NASA Wildfire SensorWeb was employed to collect data on the burn scars resulting from the Simi Valley, Val Verde and Piru fires in Southern California. MODIS active fire detections for the duration of the event were used to target an acquisition by the ALI and Hyperion instruments onboard EO-1. Such data are employed by the USDA Forest Service for Burned Area Emergency Rehabilitation mapping. BAER maps are used to target high risk areas for erosion control treatments. In this image, burned areas appear red while the unburned areas appear green. The blue burn perimeter vector is based on ground data.

POC:
C. Justice,
R. Sohlberg et al.

Sensor Web Concept

Terra/Aqua MODIS Low-Resolution Data (250 m to 1 km/pixel)

Science Agents

Science Event Manager
Processes alerts and prioritizes response observations

EO-1 Hyperion & ALI then obtain High- Resolution Data of Event (10-30 m/pixel)

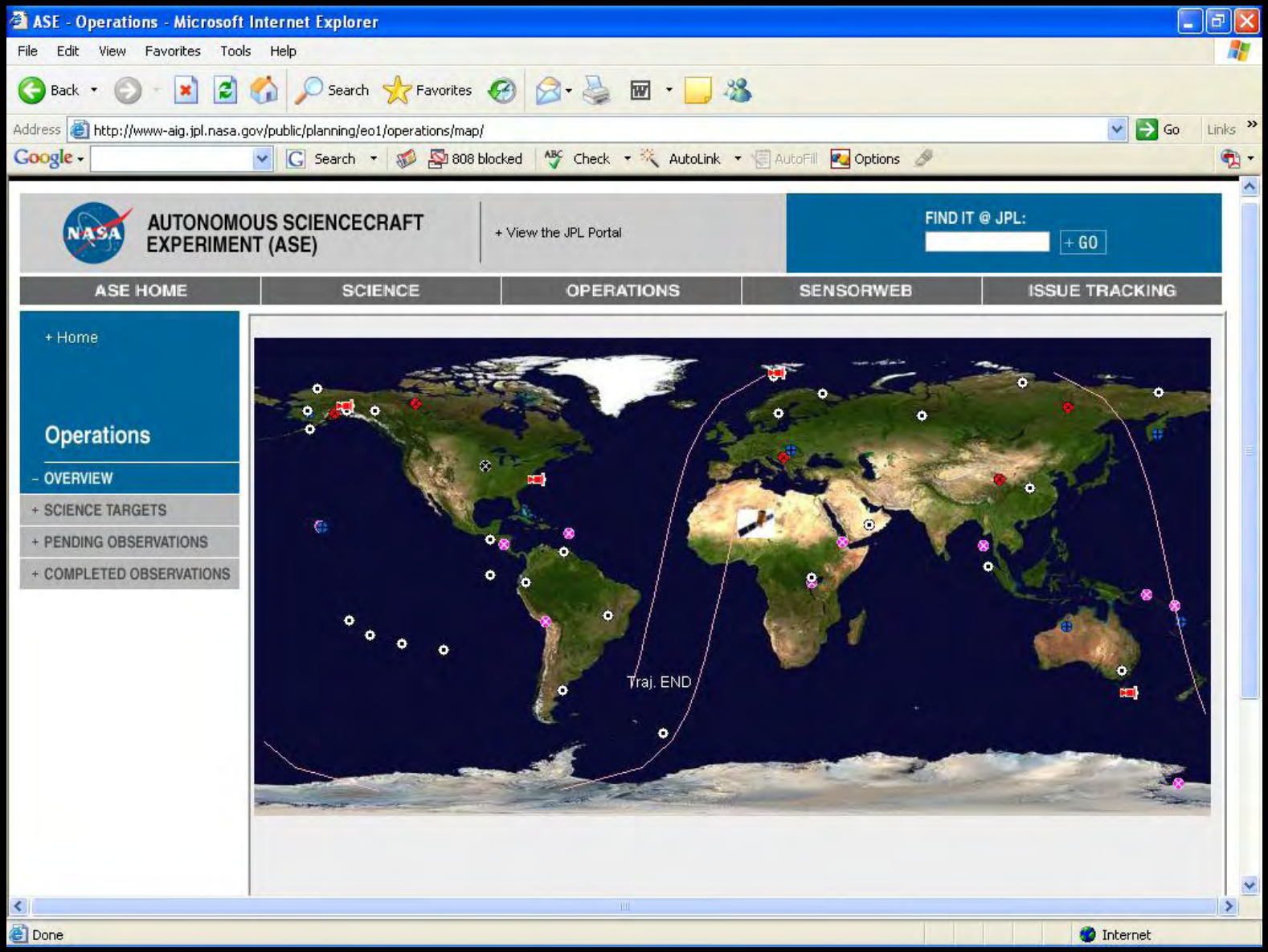
Rapid downlink of relevant data

In-situ assets

- Volcanoes – Kilauea, HI; Mt. Erebus, Antarctica
- Flooding – Avra Valley, AZ
- Lake Freeze/thaw – Sparkling Lake & Trout Lake, WI

No human in the loop!

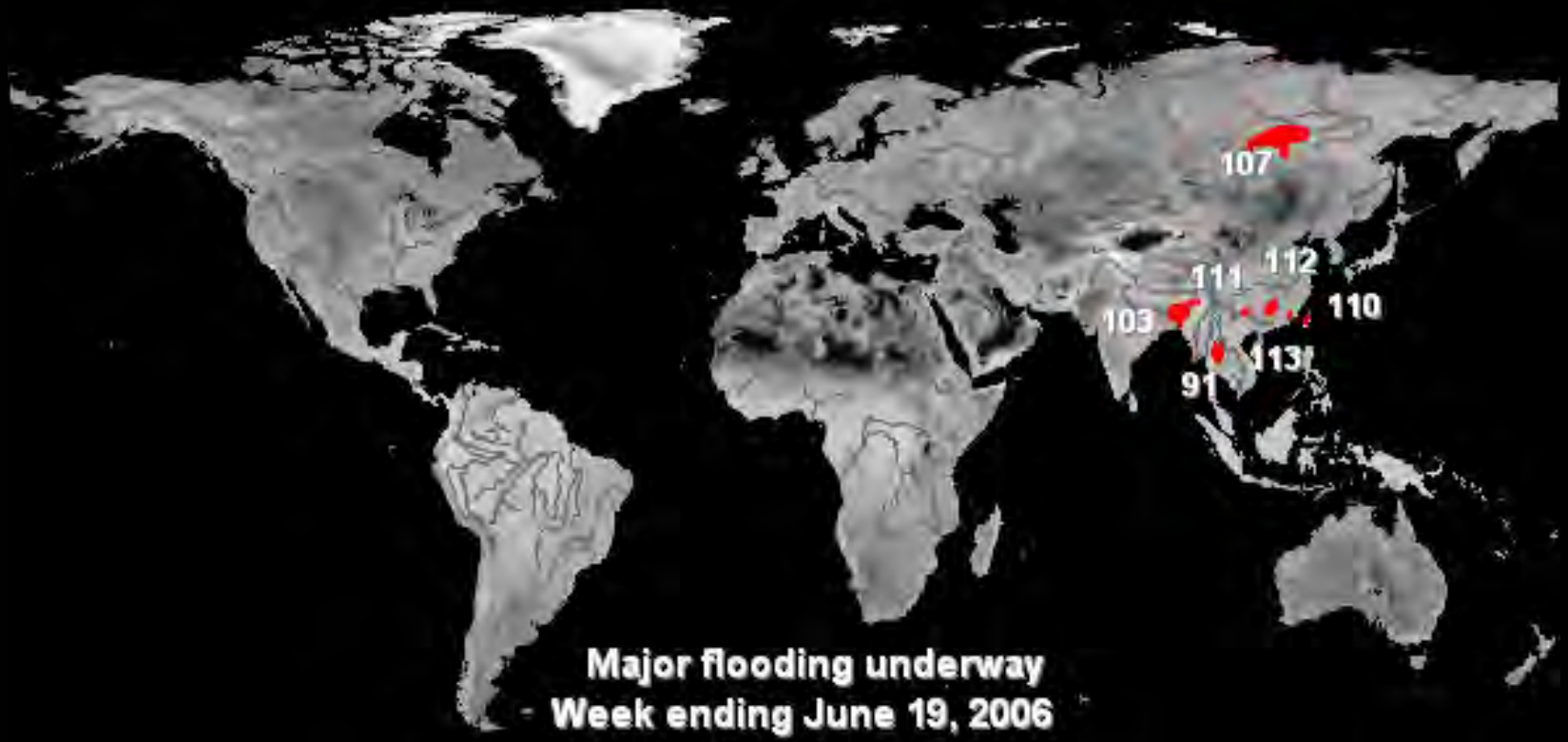
Sensorweb Map



Past Volcano Events (Sept-Oct 2005)

Target	Dates (DOY)	# of Observations
Mt. Erebus	281-286	5 in 6 days
	267-271	4 in 5 days
Shiveluch	264-275	7 in 11 days
	281-285	5 in 5 days
Erta Ale	284-286	3 in 3 days
	273-279	5 in 6 days
Mt St Helens	257-261	4 in 4 days
	243-245	3 in 3 days
Belinda	275-284	6 in 9 days

Floods - Detection



Dartmouth-Flood Observatory

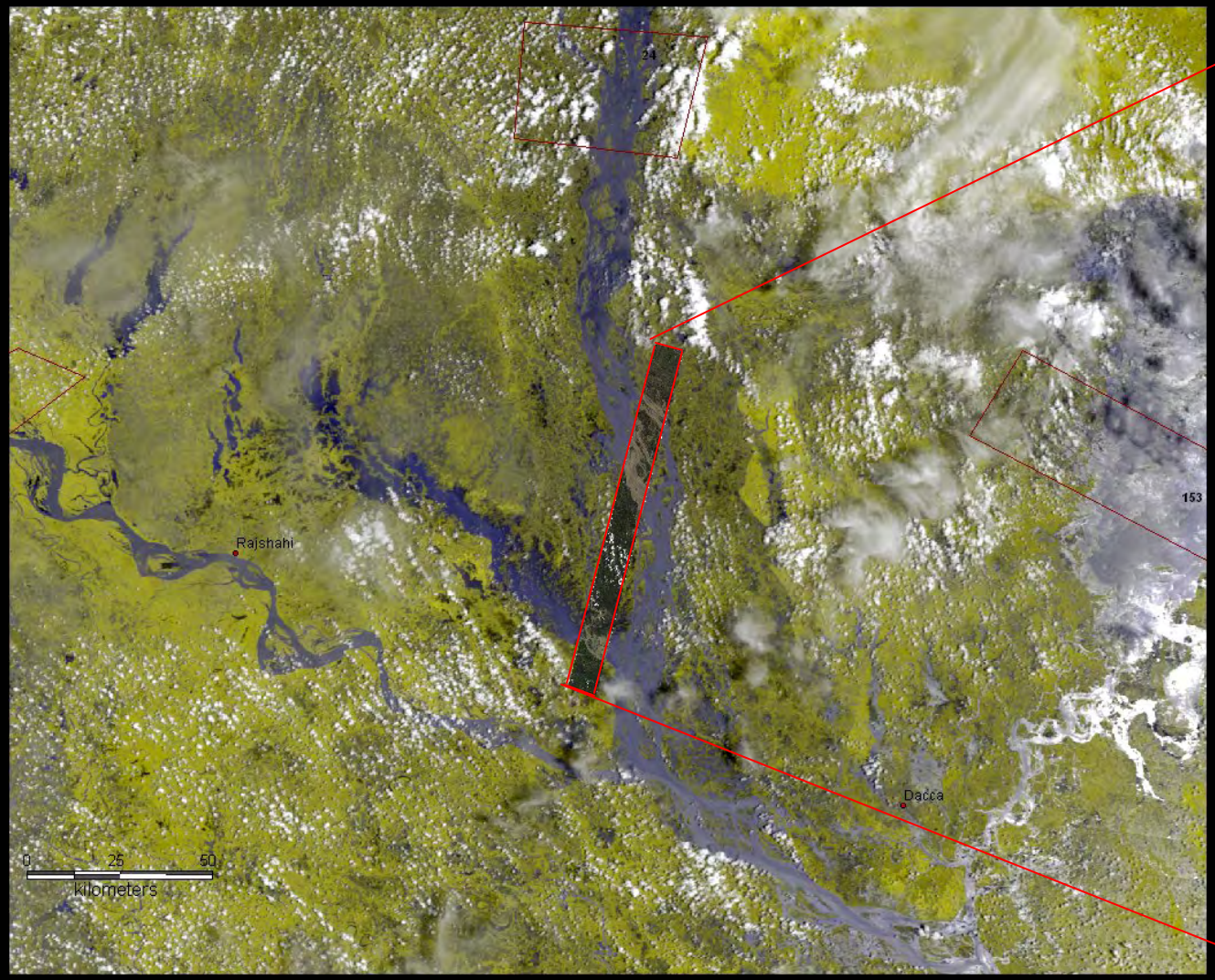
- The DFO in collaboration with JPL processes QuikSCAT Scatterometer, MODIS, and AMSR-E data to assess surface water conditions.
- Quikscat:
  - VV/HH ratio is used to assess surface water properties of the areas in 0.25 lat/lon degree bins
  - The 7 day running mean is used to dampen effects of short-duration rainfall over urban areas.
  - This data is then compared to the seasonal (90 day) average of the previous year to screen out wetlands.

POC:
Brakenridge/DFO
Ngiem/JPL

Flood alerts are then used to retask EO-1.

EO-1 Hyperion Image Brahmaputra Aug 6, 2003

MODIS Image Brahmaputra, India Aug 6, 2003



250M resolution

(10M ALI Pan band possible) 30M resolution

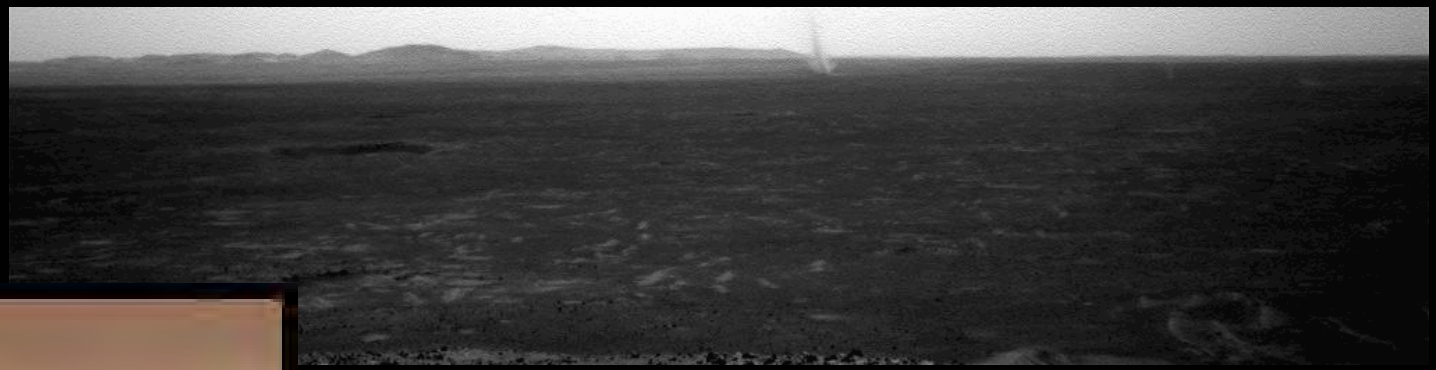
Sensorweb Applications

Discipline	Source	Detector
Volcanos	**MODIS (Terra Aqua)**	**MODVOLC, U Hawaii**
	GOES	**GOESVolc**
	Air Force Weather Advisory	**Volcanic Ash Alerts**
	International FAA	**Volcanic Ash Advisories**
	Tungurahua, Reventador	In-situ instruments, Harvard, UNH
	Hawaiian Volcano Observatory, **Erebus Volcano Observatory,** Rabaul Volcano Observatory, ...	Sensor alerts
Floods	**QuikSCAT**	**Dartmouth Flood Observatory**
	MODIS	**Dartmouth Flood Observatory**
	AMSR	**Dartmouth Flood Observatory**
Cryosphere	**QuikSCAT (Nghiem)**	**Snow/Ice, JPL/Nghiem**
	Wisconsin Lake Buoys	**UW Dept. Limnology**
Forest fires	MODIS (Terra, Aqua)	RAPIDFIRE, U. MD, MODIS Rapid Response
Dust Storms	MODIS (Terra, Aqua)	Naval research Laboratory, Monterey
Clouds	**EPOS**	**DoD**

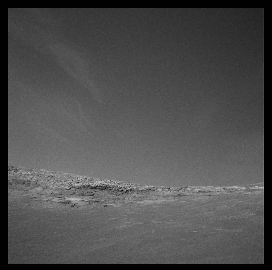
Ongoing Infusions

Mars Exploration Rovers

- Autonomous Science technology software is being infused into the Mars Exploration Rovers Mission to detect and summarize imagery containing clouds and dust devils
  - Planned upload in Summer 2006



Clouds



Dust Devils
8 Aug 2005

S. Chien, A. Fukunaga, A. Castaño, R. Castaño, J. Biesiadecki, R. Greeley, M. Lemmon

Dust Devil Tracking

- Red boxes indicate detected dust devils.

Cloud Detection

Sky detector Goals

Adaptive to horizon line:

- Non-horizontal skyline
- Soft horizon
- Segmented skyline

Robustness to environmental conditions:

- Clouds
- Overcast
- Clear sky

Robustness to optical effects:

- Radiometric effects
- Saturation
- Segmented sky

Cloud detector Goals

Robustness to cloud features:

- Clear/wispy clouds
- Any shape
- Any size
- Any location

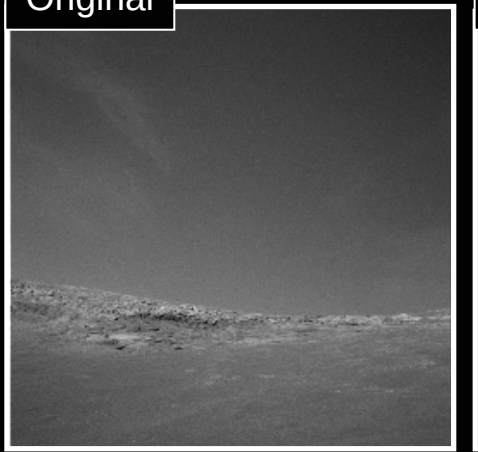
Versatile threshold:

- Manual
- Function of image noise

Data reduction:

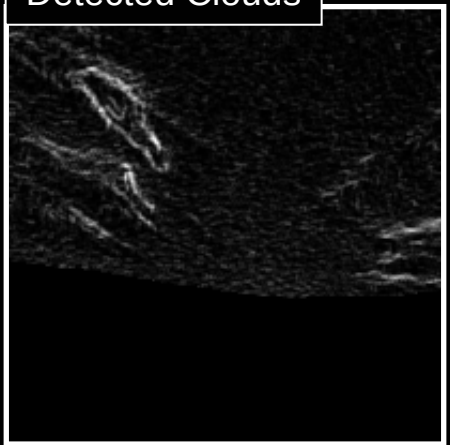
- Large hit ratio
- Smaller download image
- Data product driven

Original



Detected sky

Detected Clouds



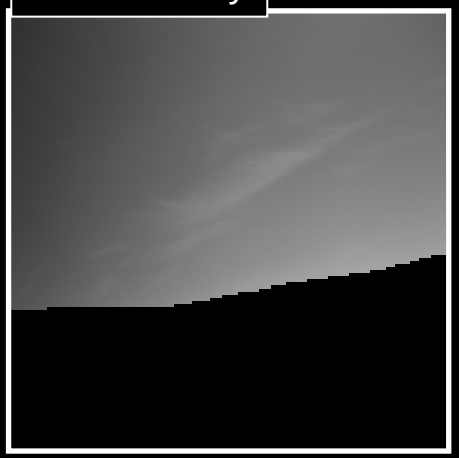
Product

Cloud Detection

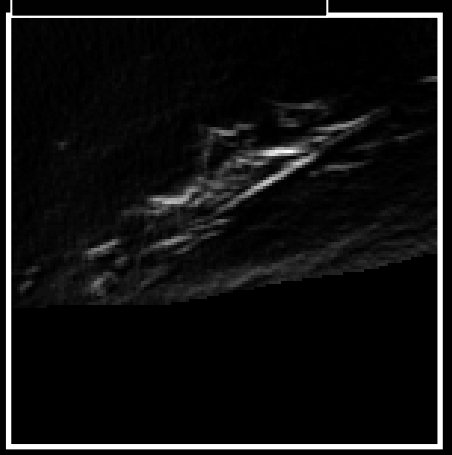
Detection of evident cloud

Original

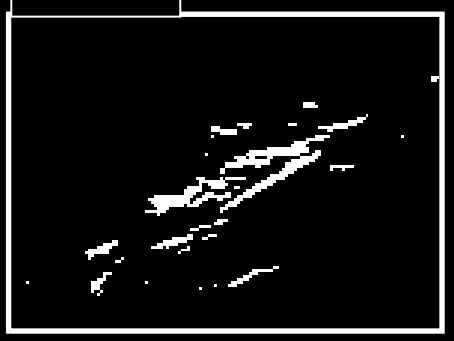
Detected sky



Detected Clouds



Product

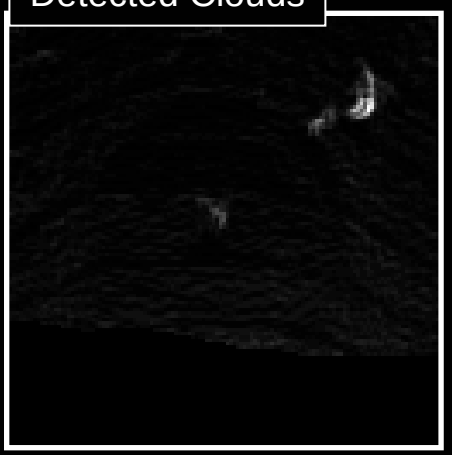


Detection of wispy cloud

Original

Detected sky

Detected Clouds



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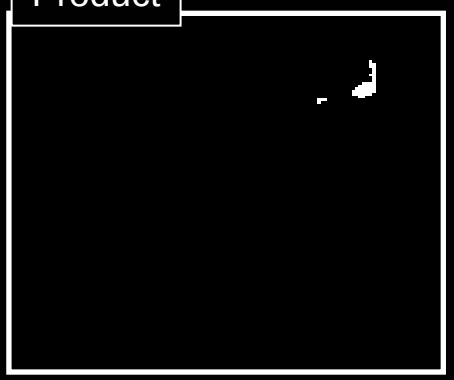
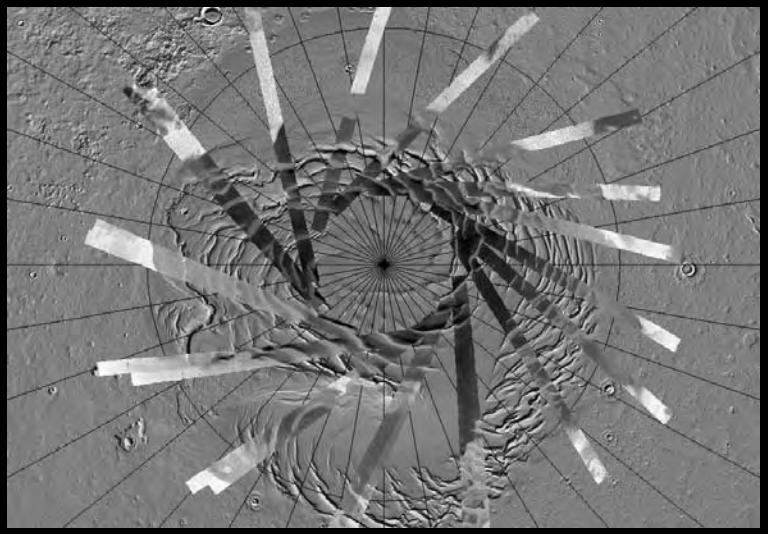


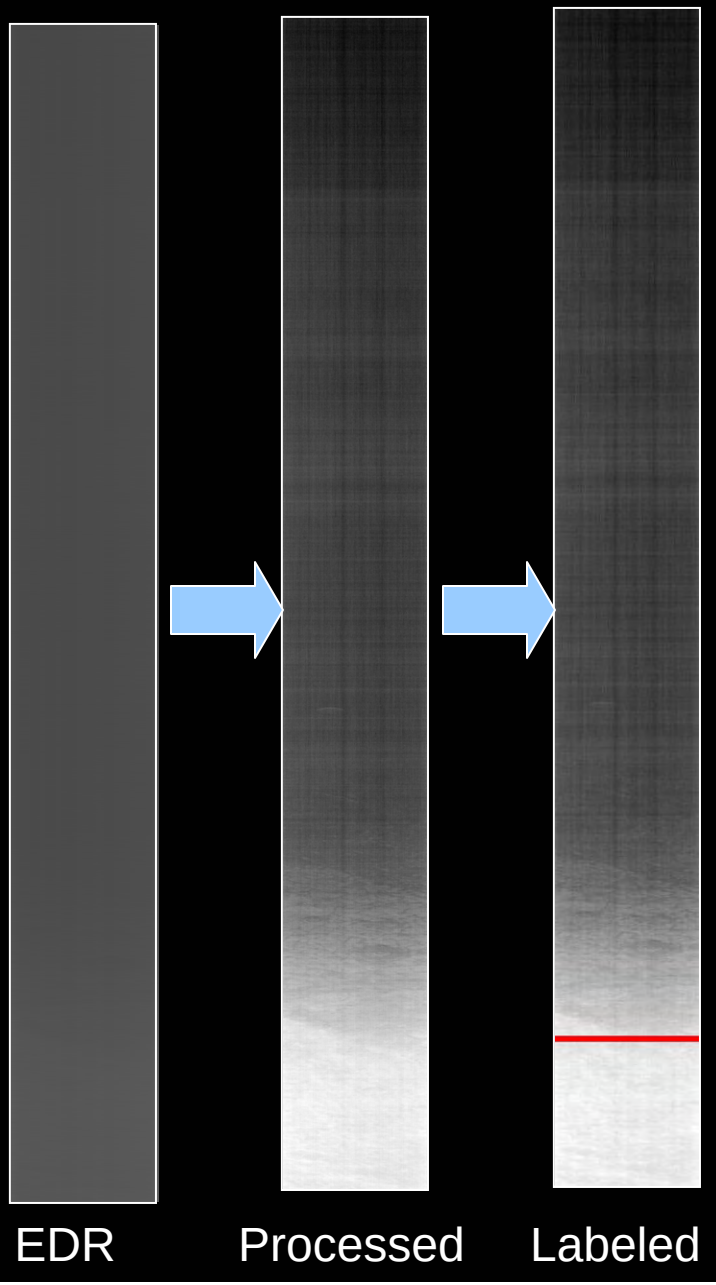
Mars Odyssey



Mars, North Pole, THEMIS orbits 4319-4399 (northern summer)

JMARS - Noel Gorelick/ASU

- THEMIS PI (Christensen) requested onboard science capabilities for Mars Odyssey 2nd extended mission (Fall 2006):
  - Dust storms, clouds, thermal anomalies, polar volatiles



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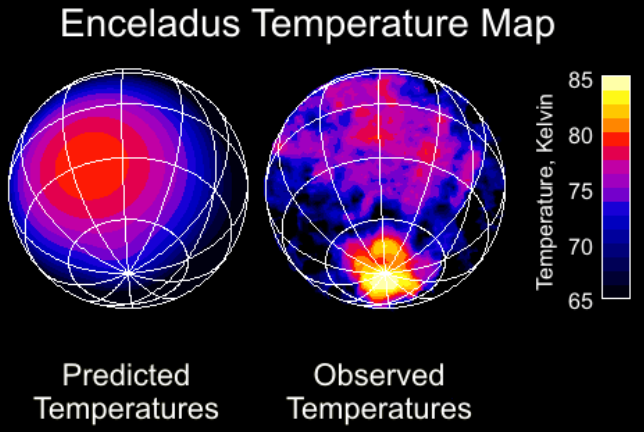
P. Christensen, A. Ivanov, T. Titus, J. Bandfield, N Gorelick

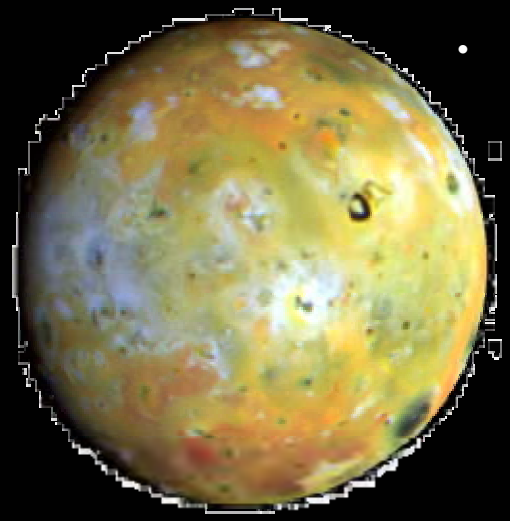
Big Payoff Applications for Autonomy

- Active Volcanism in The Solar System
- Tracking Surface Changes on Europa
- Europa Cryobot
- Comet Lander and Sample Return
- Mars Robotic Outpost

Active Volcanism in the Solar System

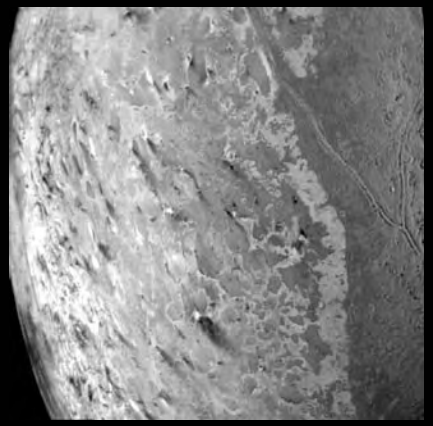
Left and right: *Cassini* images of an active Enceladus where cryo-volcanism is taking place, possibly driven by hot silicates (Spencer *et al.,* 2006, LPSC37; Matson *et al.,* 2006, LPSC37)



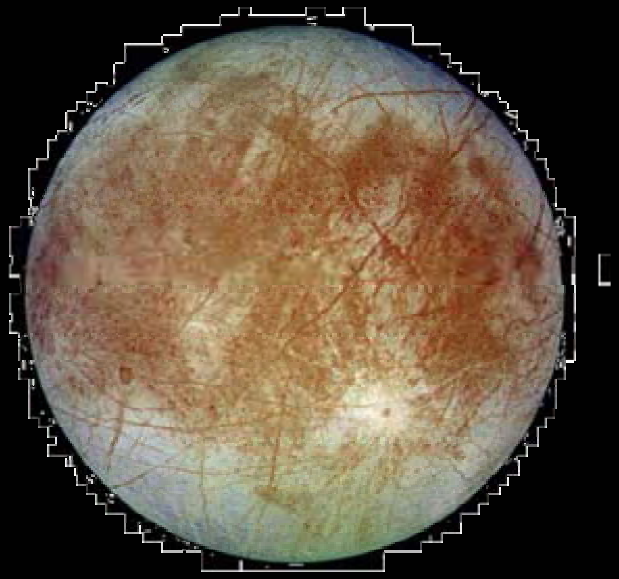


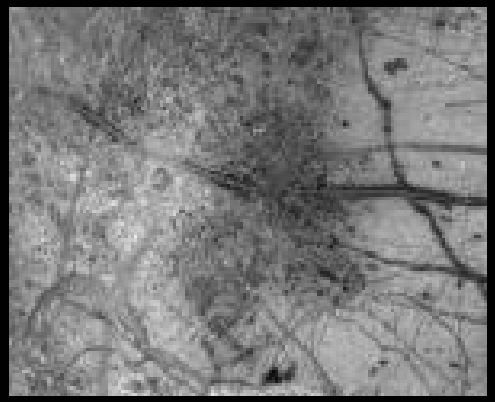
- Left: Io, the most volcanically active body in the Solar System, as seen by *Galileo.*

- Right, below: cryovolcanism observed on Triton by *Voyager 2.*



Tracking Surface Changes on Europa





- Autonomy used to identify areas of change
- Autonomy used to determine science priority or compress
  - Extract and track segmentation of boundaries
  - Extract and track region boundaries

Unknowns and Impact on Operations – Europa Cryobot

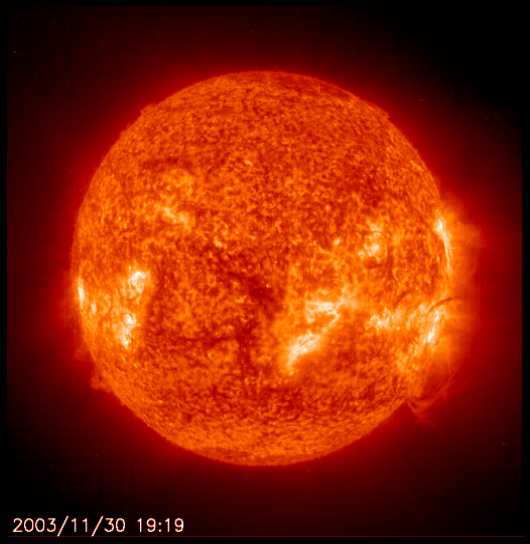
- Thickness and composition of ice-cap
  - Energy expended to penetrate surface
  - Data volume and type collected
  - Ability to communicate while below cap (reliability, rate)
  - Effectiveness of melting strategies (fast v. Slow)
- Properties of underground ocean
  - Energy and time cost to move/explore
  - Effectiveness of sensors (reliability, range, discriminability)
  - Ability to communicate
  - Predictability of above

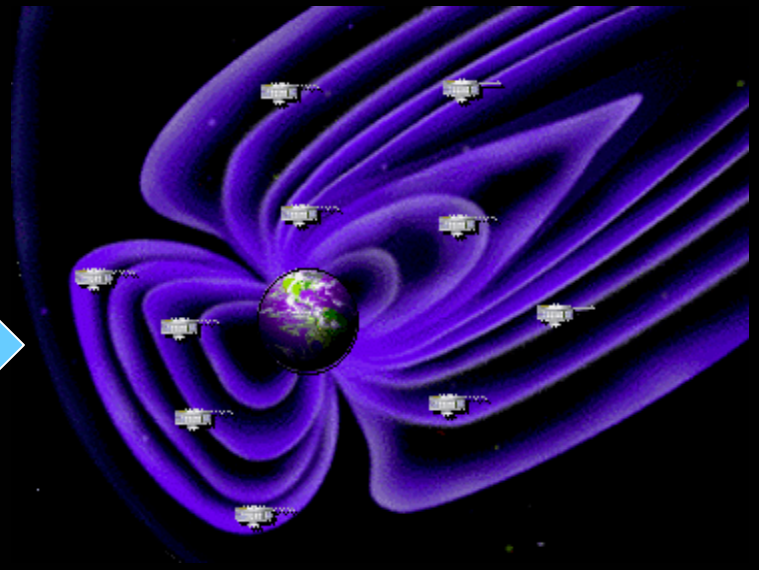
Comet Lander

Examples of Unknowns and Impact on Planning

- Hardness of surface
  - Time to drill to specified depth
  - Power consumption of drilling activities
- Outgassing events – high science value to image
- Outgassing properties of comet under solar illumination
  - Affects lighting for pictures
  - May affect communications links

Future - Space Weather

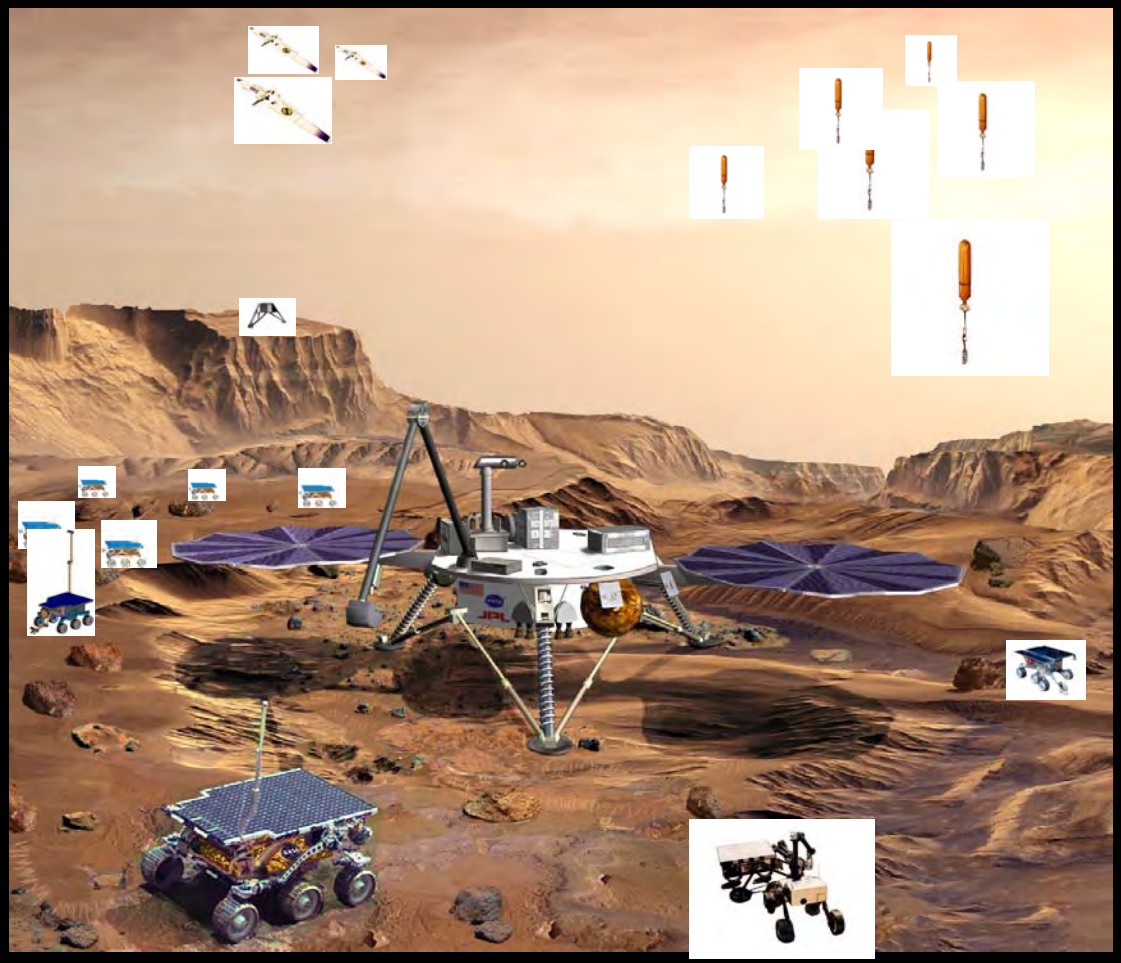




Sun-pointed instruments detect solar activity such as Coronal Mass Ejection (CME)

Earth orbiting Magnetospheric Observers automatically respond by reconfiguring to acquire best data

Mars Robotic Outpost



- Long-term environmental changes (general warming trend)
- Medium-term environmental changes (seasons)
- Shorter-term environmental changes (storms)
- Hardware degradation
- Communications performance
- Mobility
- Sensor effectiveness

…

Adaptive, self-organizing Exploration Agents

- conduct extended (decades long) environmental and geological Martian survey

Conclusions

- ASE is a flight proven tool that dramatically increases science return and reduces operations cost
  - Combines onboard science analysis, planning, and execution to achieve a >100 fold increase in science return on EO-1
- ASE enables new types of missions, science, and operations
  - Enables missions exploring hostile, dynamic, unknown environments
    - Venus Surface, Europa Subsurface Ocean, Comet Lander, Titan Aerobot
  - Captures dynamic science events
  - Using ASE, mission operations can be automated
- ASE is readily adaptable to other missions and commercial uses
  - Currently ASE being infused into
    - Mars Exploration Rovers (MER)
    - Mars Odyssey (THEMIS)
  - ASE components previously adapted to range of missions including Techsat-21, Three Corner Sat

Information/Acknowledgements

- Web Sites: ase.jpl.nasa.gov and sensorweb.jpl.nasa.gov
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